Monte Carlo event generators for LHC

Overview

- What is a Monte Carlo event generator?
  - What does “Monte Carlo” mean?
  - What do you get out of the event generator?
- How does the MC describe a scattering event?
  — an event and its parts according to the MC
- Limitations and approximations
- Implementing new processes
- A few useful things to keep in mind when simulating

The Monte Carlo method

We want to approximate an integral using random numbers. Let u_i be uniformly distributed random numbers, $u_i \in (a, b)$.

The law of large numbers says that we can use the average of the function at the random points:

$$\frac{1}{N}\sum_{i=1}^{N} f(u_i) \rightarrow \frac{1}{b-a}\int_a^b f(u)du \quad \text{as} \quad N \rightarrow \infty$$

Moreover, the central limit theorem says that the sum's standard deviation goes as $1/\sqrt{N}$.

(It actually says that the sum of N random numbers follows a normal distribution for large N.)

This is the basis for Monte Carlo — we know how to approximate the integral and the error we make.

The Monte Carlo method 2

This gives an estimate of the integral
—and generates samples u_i from the function $f(u)$
(i.e. *events*)

However, the events are uniformly distributed in u

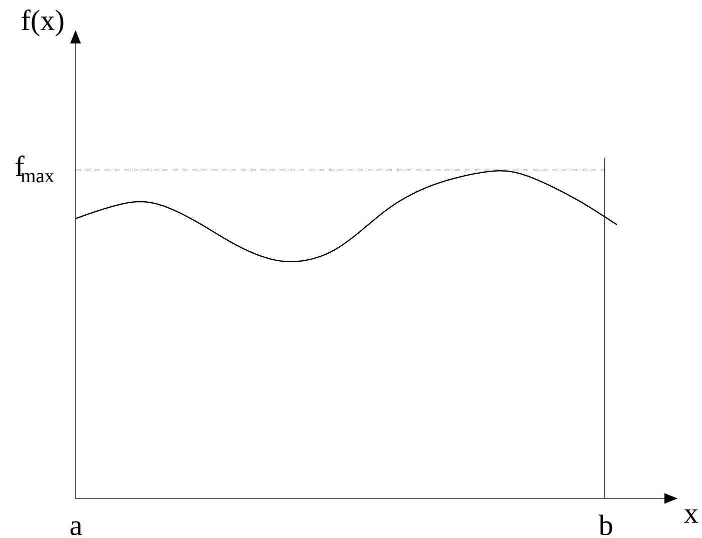
$\longrightarrow$ They do not correspond to physical events!

$\longrightarrow$ Can be used to histogram distributions if using $f(u_i)$ as weighting factor

So, how to generate *unweighted* events and still get an estimate of the integral?

Event generation

Consider a bounded function $f(x)$ on $x \in (a,b)$ and throw random points at rectangle $x \in (a,b)$, $y = R\,f_{max}$, $R \in (0,1)$



Prob(random point is under curve) $= \dfrac{\int_a^b f(x)dx}{f_{max} \times (b-a)}$

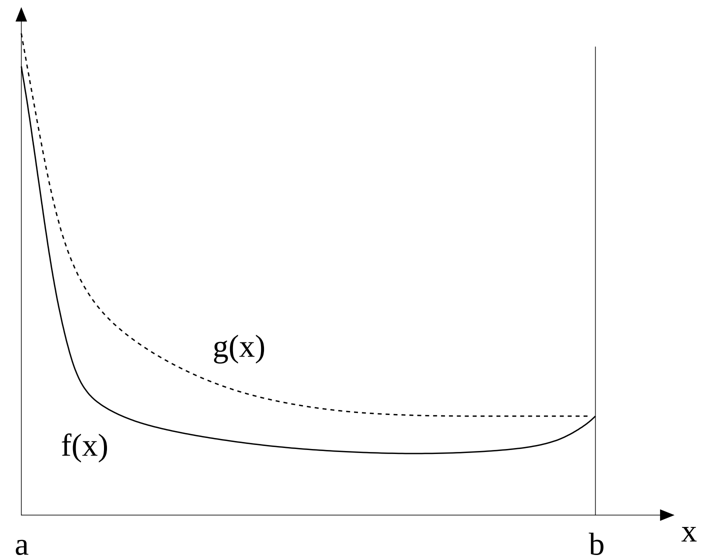
If under curve [$R < f(x)/f_{max}$], keep x, otherwise generate new

$\longrightarrow$ gives estimate of the integral $\int_a^b f(x)dx$

$\longrightarrow$ *and at the same time* samples from distribution $f(x)$

Event generation 2

The above method is usually not very efficient:



Now pick x randomly from “simple enough” distribution $g(x)$ instead of uniformly

$$\text{Prob(random point is under curve)} = \frac{\int_a^b f(x)dx}{\int_a^b g(x)dx}$$

If $R < f(x)/g(x)$, keep x, otherwise generate new

$\longrightarrow$ Gives an estimate of the integral and samples $f(x)$, but in a more efficient way

- MC is a way to generate samples from a probability distribution and at the same time obtain a numerical evaluation of the integral

  (A sample = a specifi c value for each integration variable, distributed according to the integrand interpreted as a probability distribution)

- More efficient than deterministic quadrature only in many dimensions

- But it allows arbitrarily complicated integration boundaries (e.g. experimental cuts)

- One can easily get distributions (e.g. differential cross sections) in any of the variables without having to redo the integration to histogram another variable!

- It's important to have a good random number generator

  (PYTHIA spend 30% of the CPU time in generating random numbers)

What do you get from an event generator?

- Complete events with particles (not tracks) at the hadron level
  (4-vectors, identity, info on origin)
- Cross section
  (total σ within cuts, differential σ if histogrammed)
- This is what would kind of be entering the detector
  ALL particles — no efficiency corrections!
- Experimentalists: interface to detector simulation

  Theorists: take it as it is (do crude jet finding and kinematic cuts)

  Both: some event reconstruction may be needed

Example event record

Event listing (summary)

I	particle	KS	KF	orig	p_x	p_y	p_z	E	m
1	!p+!	21	2212	0	0.000	0.000	7000.000	7000.000	0.938
2	!p+!	21	2212	0	0.000	0.000	-7000.000	7000.000	0.938
3	!u!	21	2	1	0.915	0.480	2619.257	2619.258	0.000
4	!g!	21	21	2	-0.389	1.146	-1123.309	1123.310	0.000
5	!g!	21	21	3	-3.594	-8.887	136.830	137.165	0.000
6	!g!	21	21	4	-2.297	-2.528	-401.440	401.454	0.000
7	!tbar!	21	-6	0	-73.000	80.531	-258.699	330.702	174.997
8	!t!	21	6	0	67.110	-91.946	-5.910	207.918	173.888
9	!W-!	21	-24	7	21.550	68.583	-153.129	188.397	82.927
10	!bbar!	21	-5	7	-94.550	11.948	-105.570	142.305	4.800
11	!W+!	21	24	8	1.976	-66.959	51.898	117.190	80.948
12	!b!	21	5	8	65.133	-24.986	-57.808	90.728	4.800
13	!e-!	21	11	9	44.421	19.442	-104.352	115.068	0.001
14	!nu_ebar	21	-12	9	-24.003	48.233	-47.428	71.777	0.000
15	!dbar!	21	-1	11	16.403	1.463	-18.363	24.668	0.330
16	!u!	21	2	11	-8.185	-59.849	55.833	82.258	0.330

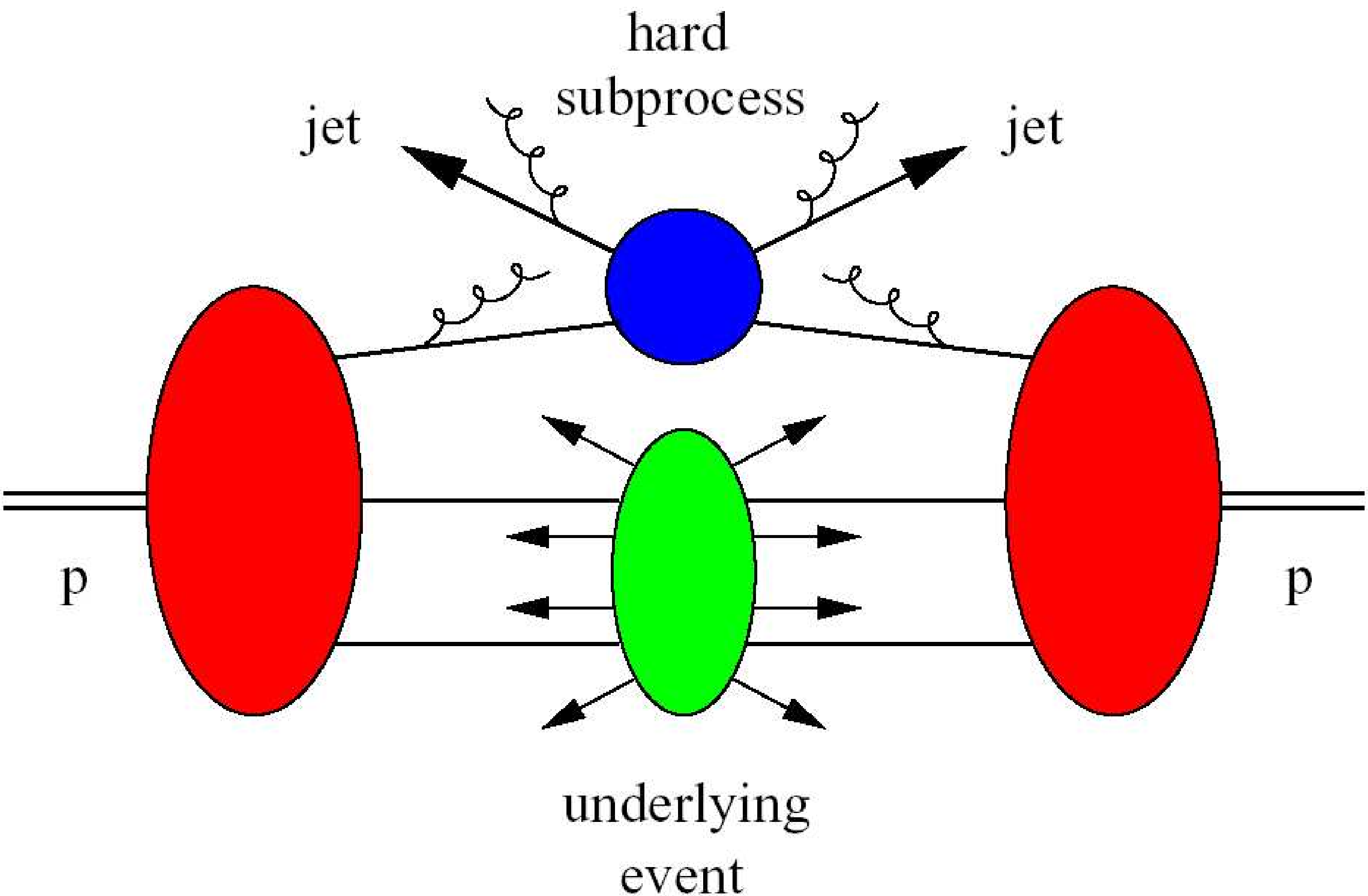
. . . continued

17	(W-)		11	-24	9	20.418	67.675	-151.781	186.845	82.927
18	(W+)		11	24	11	8.218	-58.387	37.470	106.926	80.948
19	nu_ebar		1	-12	14	-23.998	48.224	-47.420	71.764	0.000
20	e-		1	11	13	44.040	19.315	-103.241	113.892	0.001
21	gamma		1	22	13	0.377	0.136	-1.120	1.189	0.000
22	(u)	A	12	2	3	3.169	7.628	2276.660	2276.675	0.330
23	(g)	I	12	21	3	1.846	-1.046	172.351	172.364	0.000
24	(g)	I	12	21	3	-0.599	-0.190	10.322	10.341	0.000
25	(g)	I	12	21	0	0.410	-1.203	8.919	9.009	0.000
26	(g)	I	12	21	0	2.735	-4.154	59.775	59.981	0.000
27	(g)	I	12	21	0	-2.221	-3.651	127.034	127.106	0.000
28	(g)	I	12	21	0	-0.655	-0.708	54.713	54.722	0.000
29	(g)	I	12	21	0	3.975	2.039	144.416	144.485	0.000
30	(g)	I	12	21	0	0.430	0.312	17.812	17.820	0.000
31	(g)	I	12	21	0	0.655	0.708	28.184	28.200	0.000
32	(g)	I	12	21	0	4.222	4.322	69.750	70.011	0.000
33	(g)	I	12	21	0	3.097	-2.281	12.024	12.624	0.000
34	(g)	I	12	21	0	2.221	3.651	9.531	10.445	0.000
35	(g)	I	12	21	0	2.815	6.945	16.476	18.100	0.000
36	(g)	I	12	21	0	0.916	2.228	2.582	3.532	0.000
37	(g)	I	12	21	0	0.126	2.889	2.207	3.638	0.000
38	(g)	I	12	21	0	-0.410	1.203	2.247	2.581	0.000

…and the end

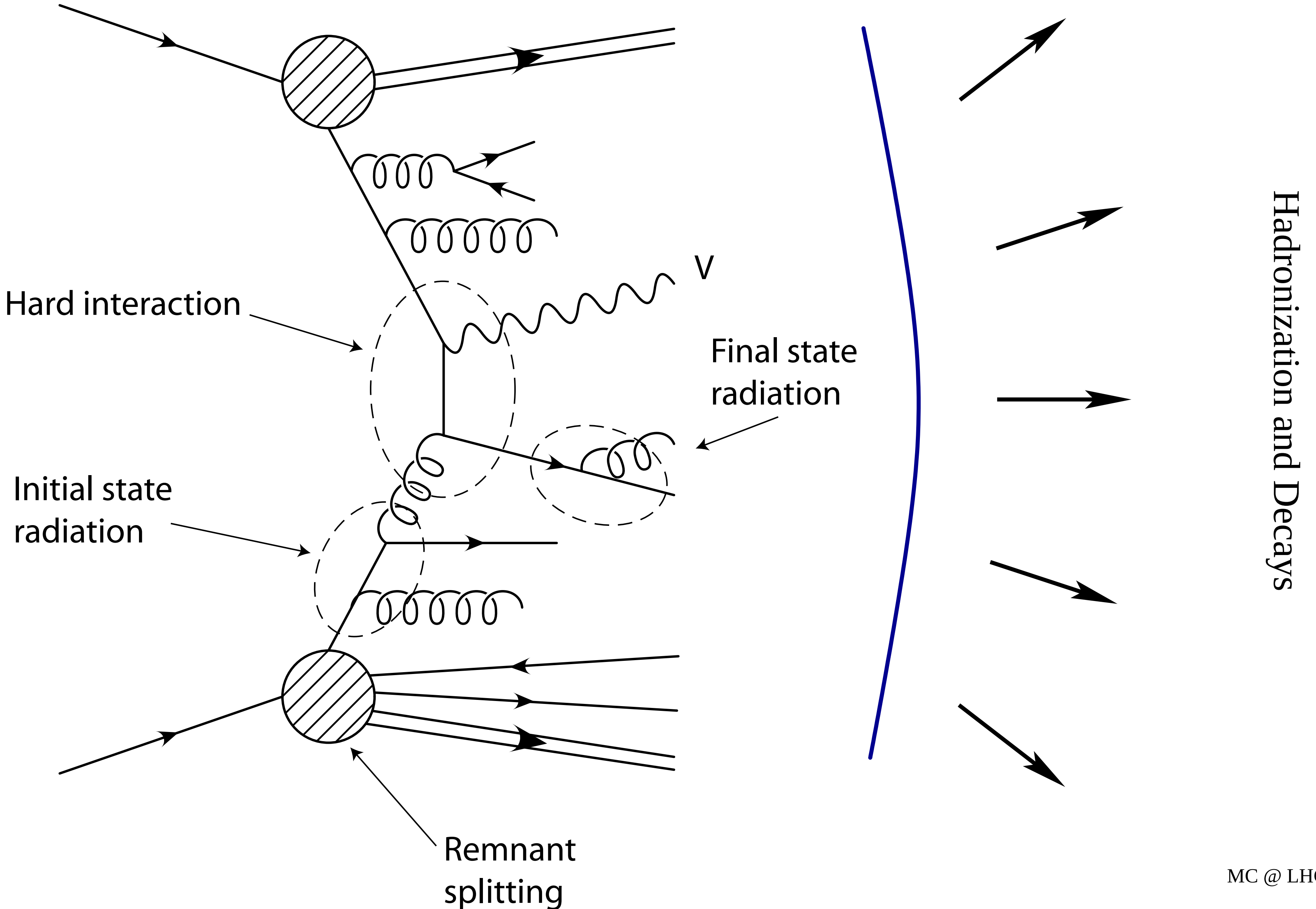
```
1525 pi-         1  -211 1495   8.852   12.031  4.461  15.590  0.140
1526 pi+         1   211 1495   2.965    4.037  1.098   5.130  0.140
1527 gamma       1    22 1496  13.444   17.381  6.036  22.788  0.000
1528 gamma       1    22 1496  10.724   14.455  4.592  18.575  0.000
1529 K-          1  -321 1498  -9.608   -2.079  4.520  10.831  0.494
1530 (pi0)      11   111 1498  -9.946   -1.818  5.293  11.413  0.135
1531 pi+         1   211 1499  -2.443   -0.507  1.414   2.871  0.140
1532 (pi0)      11   111 1499  -3.288   -1.055  2.087   4.037  0.135
1533 gamma       1    22 1507  -0.009   -0.033 -0.028   0.044  0.000
1534 gamma       1    22 1507   0.039   -0.083  0.145   0.171  0.000
1535 gamma       1    22 1508   0.025   -0.349  0.942   1.005  0.000
1536 gamma       1    22 1508   0.047   -0.364  0.656   0.752  0.000
1537 gamma       1    22 1521   0.072    0.085  0.024   0.114  0.000
1538 gamma       1    22 1521   4.104    5.869  2.471   7.576  0.000
1539 gamma       1    22 1522   2.291    3.037  1.256   4.006  0.000
1540 gamma       1    22 1522   3.940    4.995  2.214   6.736  0.000
1541 gamma       1    22 1530  -0.740   -0.156  0.363   0.839  0.000
1542 gamma       1    22 1530  -9.207   -1.662  4.930  10.575  0.000
1543 gamma       1    22 1532  -1.190   -0.364  0.825   1.493  0.000
1544 gamma       1    22 1532  -2.098   -0.691  1.262   2.544  0.000
==================================================================
```

Example of LHC event



(from HERWIG lecture by B. Webber at FNAL, October 25, 2004)

Or...


V
Hard interaction
Final state
radiation
Initial state
radiation
Remnant
splitting
Hadronization and Decays

Steps involved

1. Hard subprocess (Matrix Elements)

   $\longrightarrow$ defines what is produced and the kinematics

2. Decay unstable particles
3. Initial and final state parton showers

   $\longrightarrow$ collinear parton radiation; mainly builds up jets

4. Multiple (soft) parton–parton interactions

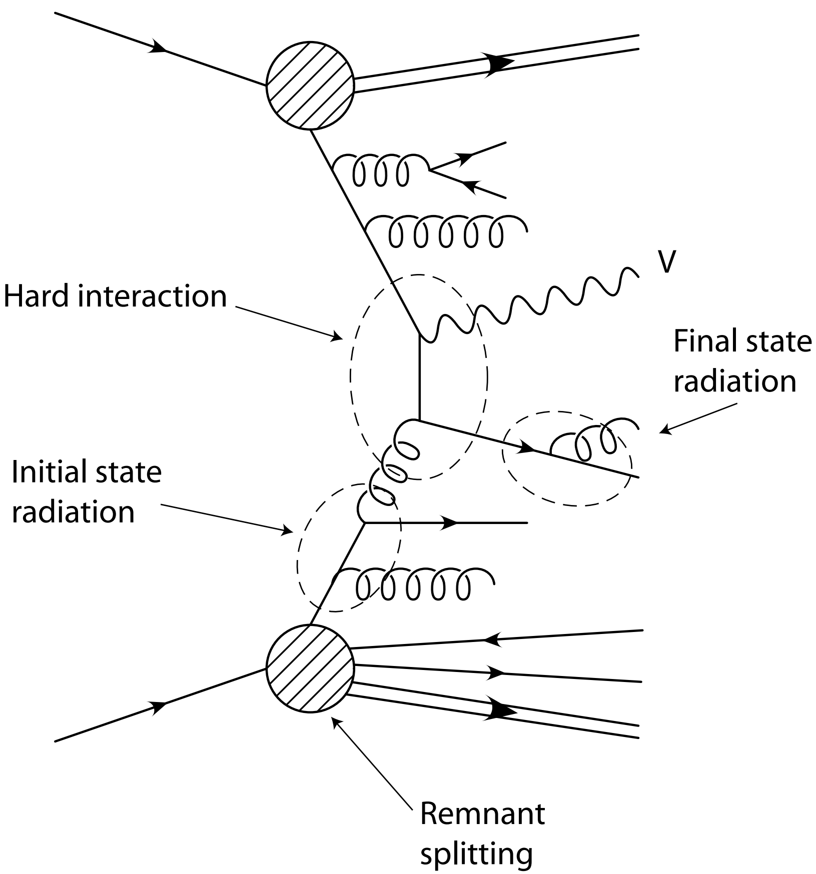
   $\longrightarrow$ build up underlying event

5. Keep track of color flow including remnants
6. Hadronize

   $\longrightarrow$ Lund strings (PYTHIA); cluster (HERWIG)

7. Decay

Hard subprocess: Matrix Elements



Have to choose subprocesses

- Can select one or many—only choose production channels and decays that you are interested in!
  (Simulate background separately and weight them together with cross sections)
- MC chooses subprocess according to relative cross sections
- Only tree-level processes, mostly $2 \to 2$, some $2 \to 3$

Subprocesses, Part 1

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$

No.	Subprocess
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi\gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi\gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$

No.	Subprocess
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$

Subprocesses, Part 2

No.	Subprocess
Photon-induced:	
33	$f_i\gamma \to f_i g$
34	$f_i\gamma \to f_i\gamma$
54	$g\gamma \to f_k\bar{f}_k$
58	$\gamma\gamma \to f_k\bar{f}_k$
131	$f_i\gamma^*_T \to f_i g$
132	$f_i\gamma^*_L \to f_i g$
133	$f_i\gamma^*_T \to f_i\gamma$
134	$f_i\gamma^*_L \to f_i\gamma$
135	$g\gamma^*_T \to f_i\bar{f}_i$
136	$g\gamma^*_L \to f_i\bar{f}_i$
137	$\gamma^*_T\gamma^*_T \to f_i\bar{f}_i$
138	$\gamma^*_T\gamma^*_L \to f_i\bar{f}_i$
139	$\gamma^*_L\gamma^*_T \to f_i\bar{f}_i$
140	$\gamma^*_L\gamma^*_L \to f_i\bar{f}_i$
80	$q_i\gamma \to q_k\pi^\pm$
Light SM Higgs:	
3	$f_i\bar{f}_i \to h^0$
24	$f_i\bar{f}_i \to Z^0h^0$
26	$f_i\bar{f}_j \to W^\pm h^0$

No.	Subprocess
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i\bar{f}_i \to \gamma h^0$
111	$f_i\bar{f}_i \to gh^0$
112	$f_i g \to f_i h^0$
113	$gg \to gh^0$
121	$gg \to Q_k\bar{Q}_k h^0$
122	$q_i\bar{q}_i \to Q_k\bar{Q}_k h^0$
123	$f_if_j \to f_if_jh^0$
124	$f_if_j \to f_kf_lh^0$
Heavy SM Higgs:	
5	$Z^0Z^0 \to h^0$
8	$W^+W^- \to h^0$
71	$Z^0_LZ^0_L \to Z^0_LZ^0_L$
72	$Z^0_LZ^0_L \to W^+_LW^-_L$
73	$Z^0_LW^\pm_L \to Z^0_LW^\pm_L$
76	$W^+_LW^-_L \to Z^0_LZ^0_L$
77	$W^\pm_LW^\pm_L \to W^\pm_LW^\pm_L$

No.	Subprocess
BSM Neutral Higgs:	
151	$f_i\bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i\bar{f}_i \to Z^0H^0$
172	$f_i\bar{f}_j \to W^\pm H^0$
173	$f_if_j \to f_if_jH^0$
174	$f_if_j \to f_kf_lH^0$
181	$gg \to Q_k\bar{Q}_kH^0$
182	$q_i\bar{q}_i \to Q_k\bar{Q}_kH^0$
183	$f_i\bar{f}_i \to gH^0$
184	$f_ig \to f_iH^0$
185	$gg \to gH^0$
156	$f_i\bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i\bar{f}_i \to Z^0A^0$
177	$f_i\bar{f}_j \to W^\pm A^0$
178	$f_if_j \to f_if_jA^0$
179	$f_if_j \to f_kf_lA^0$

Subprocesses, Part 3

No.	Subprocess
186	$gg \to Q_k\overline{Q}_kA^0$
187	$q_i\overline{q}_i \to Q_k\overline{Q}_kA^0$
188	$f_i\overline{f}_i \to gA^0$
189	$f_ig \to f_iA^0$
190	$gg \to gA^0$
Charged Higgs:	
143	$f_i\overline{f}_j \to H^+$
161	$f_ig \to f_kH^+$
Higgs pairs:	
297	$f_i\overline{f}_j \to H^\pm h^0$
298	$f_i\overline{f}_j \to H^\pm H^0$
299	$f_i\overline{f}_i \to A^0h^0$
300	$f_i\overline{f}_i \to A^0H^0$
301	$f_i\overline{f}_i \to H^+H^-$
New gauge bosons:	
141	$f_i\overline{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i\overline{f}_j \to W'^+$
144	$f_i\overline{f}_j \to R$

No.	Subprocess
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i\overline{f}_i \to \rho^0_{tc}$
192	$f_i\overline{f}_j \to \rho^+_{tc}$
193	$f_i\overline{f}_i \to \omega^0_{tc}$
194	$f_i\overline{f}_i \to f_k\overline{f}_k$
195	$f_i\overline{f}_j \to f_k\overline{f}_l$
361	$f_i\overline{f}_i \to W^+_LW^-_L$
362	$f_i\overline{f}_i \to W^\pm_L\pi^\mp_{tc}$
363	$f_i\overline{f}_i \to \pi^+_{tc}\pi^-_{tc}$
364	$f_i\overline{f}_i \to \gamma\pi^0_{tc}$
365	$f_i\overline{f}_i \to \gamma\pi'^0_{tc}$
366	$f_i\overline{f}_i \to Z^0\pi^0_{tc}$
367	$f_i\overline{f}_i \to Z^0\pi'^0_{tc}$
368	$f_i\overline{f}_i \to W^\pm\pi^\mp_{tc}$
370	$f_i\overline{f}_j \to W^\pm_LZ^0_L$
371	$f_i\overline{f}_j \to W^\pm_L\pi^0_{tc}$
372	$f_i\overline{f}_j \to \pi^\pm_{tc}Z^0_L$
373	$f_i\overline{f}_j \to \pi^\pm_{tc}\pi^0_{tc}$
374	$f_i\overline{f}_j \to \gamma\pi^\pm_{tc}$

No.	Subprocess
375	$f_i\overline{f}_j \to Z^0\pi^\pm_{tc}$
376	$f_i\overline{f}_j \to W^\pm\pi^0_{tc}$
377	$f_i\overline{f}_j \to W^\pm\pi'^0_{tc}$
381	$q_iq_j \to q_iq_j$
382	$q_i\overline{q}_i \to q_k\overline{q}_k$
383	$q_i\overline{q}_i \to gg$
384	$f_ig \to f_ig$
385	$gg \to q_k\overline{q}_k$
386	$gg \to gg$
387	$f_i\overline{f}_i \to Q_k\overline{Q}_k$
388	$gg \to Q_k\overline{Q}_k$
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_iq_j \to d^*q_k$
168	$q_iq_j \to u^*q_k$
169	$q_i\overline{q}_i \to e^\pm e^{*\mp}$
165	$f_i\overline{f}_i(\to \gamma^*/Z^0) \to f_k\overline{f}_k$
166	$f_i\overline{f}_j(\to W^\pm) \to f_k\overline{f}_l$

Subprocesses, Part 4

No.	Subprocess
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \overline{L}_Q$
164	$q_i \overline{q}_i \to L_Q \overline{L}_Q$
Left–right symmetry:	
341	$\ell_i \ell_j \to H_L^{\pm\pm}$
342	$\ell_i \ell_j \to H_R^{\pm\pm}$
343	$\ell_i^{\pm} \gamma \to H_L^{\pm\pm} e^{\mp}$
344	$\ell_i^{\pm} \gamma \to H_R^{\pm\pm} e^{\mp}$
345	$\ell_i^{\pm} \gamma \to H_L^{\pm\pm} \mu^{\mp}$
346	$\ell_i^{\pm} \gamma \to H_R^{\pm\pm} \mu^{\mp}$
347	$\ell_i^{\pm} \gamma \to H_L^{\pm\pm} \tau^{\mp}$
348	$\ell_i^{\pm} \gamma \to H_R^{\pm\pm} \tau^{\mp}$
349	$f_i \overline{f}_i \to H_L^{++} H_L^{--}$
350	$f_i \overline{f}_i \to H_R^{++} H_R^{--}$
351	$f_i f_j \to f_k f_l H_L^{\pm\pm}$
352	$f_i f_j \to f_k f_l H_R^{\pm\pm}$
353	$f_i \overline{f}_i \to Z_R^0$
354	$f_i \overline{f}_j \to W_R^{\pm}$

No.	Subprocess
Extra Dimensions:	
391	$f\overline{f} \to G^*$
392	$gg \to G^*$
393	$q\overline{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
SUSY:	
201	$f_i \overline{f}_i \to \tilde{e}_L \tilde{e}_L^*$
202	$f_i \overline{f}_i \to \tilde{e}_R \tilde{e}_R^*$
203	$f_i \overline{f}_i \to \tilde{e}_L \tilde{e}_R^* +$
204	$f_i \overline{f}_i \to \tilde{\mu}_L \tilde{\mu}_L^*$
205	$f_i \overline{f}_i \to \tilde{\mu}_R \tilde{\mu}_R^*$
206	$f_i \overline{f}_i \to \tilde{\mu}_L \tilde{\mu}_R^* +$
207	$f_i \overline{f}_i \to \tilde{\tau}_1 \tilde{\tau}_1^*$
208	$f_i \overline{f}_i \to \tilde{\tau}_2 \tilde{\tau}_2^*$
209	$f_i \overline{f}_i \to \tilde{\tau}_1 \tilde{\tau}_2^* +$
210	$f_i \overline{f}_j \to \tilde{\ell}_L \tilde{\nu}_\ell^* +$
211	$f_i \overline{f}_j \to \tilde{\tau}_1 \tilde{\nu}_\tau^* +$
212	$f_i \overline{f}_j \to \tilde{\tau}_2 \tilde{\nu}_\tau^* +$
213	$f_i \overline{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell^*$

No.	Subprocess
214	$f_i \overline{f}_i \to \tilde{\nu}_\tau \tilde{\nu}_\tau^*$
216	$f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \overline{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \overline{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \overline{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \overline{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \overline{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \overline{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \overline{f}_i \to \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$
227	$f_i \overline{f}_i \to \tilde{\chi}_2^{\pm} \tilde{\chi}_2^{\mp}$
228	$f_i \overline{f}_i \to \tilde{\chi}_1^{\pm} \tilde{\chi}_2^{\mp}$
229	$f_i \overline{f}_j \to \tilde{\chi}_1 \tilde{\chi}_1^{\pm}$
230	$f_i \overline{f}_j \to \tilde{\chi}_2 \tilde{\chi}_1^{\pm}$
231	$f_i \overline{f}_j \to \tilde{\chi}_3 \tilde{\chi}_1^{\pm}$
232	$f_i \overline{f}_j \to \tilde{\chi}_4 \tilde{\chi}_1^{\pm}$
233	$f_i \overline{f}_j \to \tilde{\chi}_1 \tilde{\chi}_2^{\pm}$
234	$f_i \overline{f}_j \to \tilde{\chi}_2 \tilde{\chi}_2^{\pm}$

Subprocesses, Part 5

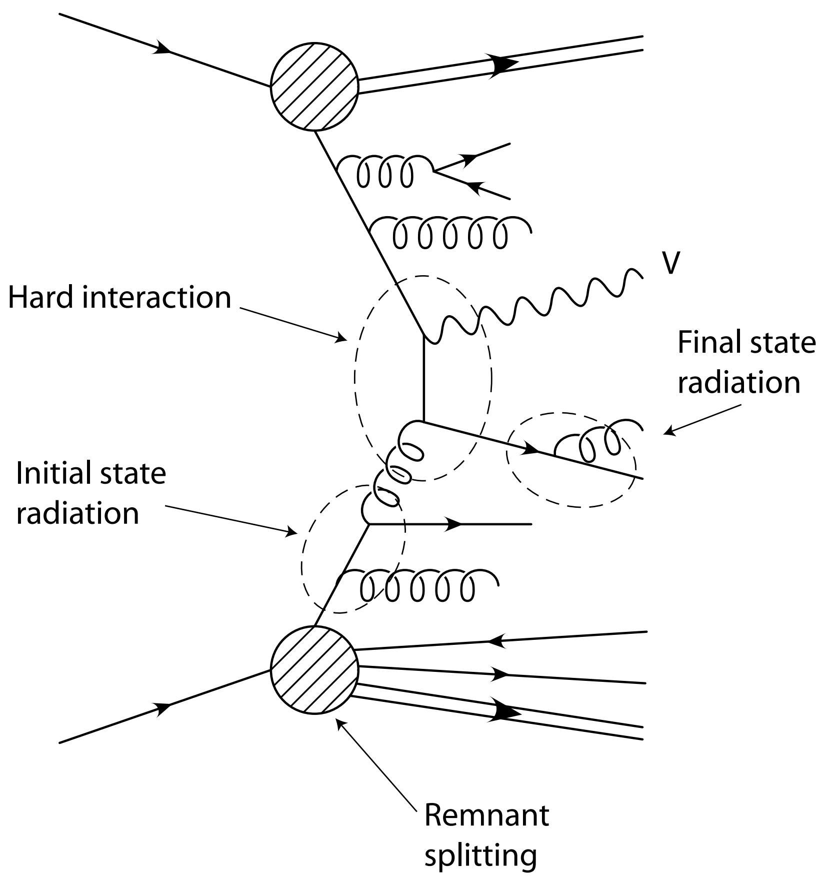
No.	Subprocess
235	$f_i\bar{f}_j \to \tilde{\chi}_3\tilde{\chi}_2^\pm$
236	$f_i\bar{f}_j \to \tilde{\chi}_4\tilde{\chi}_2^\pm$
237	$f_i\bar{f}_i \to \tilde{g}\tilde{\chi}_1$
238	$f_i\bar{f}_i \to \tilde{g}\tilde{\chi}_2$
239	$f_i\bar{f}_i \to \tilde{g}\tilde{\chi}_3$
240	$f_i\bar{f}_i \to \tilde{g}\tilde{\chi}_4$
241	$f_i\bar{f}_j \to \tilde{g}\tilde{\chi}_1^\pm$
242	$f_i\bar{f}_j \to \tilde{g}\tilde{\chi}_2^\pm$
243	$f_i\bar{f}_i \to \tilde{g}\tilde{g}$
244	$gg \to \tilde{g}\tilde{g}$
246	$f_ig \to \tilde{q}_{iL}\tilde{\chi}_1$
247	$f_ig \to \tilde{q}_{iR}\tilde{\chi}_1$
248	$f_ig \to \tilde{q}_{iL}\tilde{\chi}_2$
249	$f_ig \to \tilde{q}_{iR}\tilde{\chi}_2$
250	$f_ig \to \tilde{q}_{iL}\tilde{\chi}_3$
251	$f_ig \to \tilde{q}_{iR}\tilde{\chi}_3$
252	$f_ig \to \tilde{q}_{iL}\tilde{\chi}_4$
253	$f_ig \to \tilde{q}_{iR}\tilde{\chi}_4$

No.	Subprocess
254	$f_ig \to \tilde{q}_{jL}\tilde{\chi}_1^\pm$
256	$f_ig \to \tilde{q}_{jL}\tilde{\chi}_2^\pm$
258	$f_ig \to \tilde{q}_{iL}\tilde{g}$
259	$f_ig \to \tilde{q}_{iR}\tilde{g}$
261	$f_i\bar{f}_i \to \tilde{t}_1\tilde{t}_1^*$
262	$f_i\bar{f}_i \to \tilde{t}_2\tilde{t}_2^*$
263	$f_i\bar{f}_i \to \tilde{t}_1\tilde{t}_2^* +$
264	$gg \to \tilde{t}_1\tilde{t}_1^*$
265	$gg \to \tilde{t}_2\tilde{t}_2^*$
271	$f_if_j \to \tilde{q}_{iL}\tilde{q}_{jL}$
272	$f_if_j \to \tilde{q}_{iR}\tilde{q}_{jR}$
273	$f_if_j \to \tilde{q}_{iL}\tilde{q}_{jR} +$
274	$f_i\bar{f}_j \to \tilde{q}_{iL}\tilde{q}_{jL}^*$
275	$f_i\bar{f}_j \to \tilde{q}_{iR}\tilde{q}_{jR}^*$
276	$f_i\bar{f}_j \to \tilde{q}_{iL}\tilde{q}_{jR}^* +$
277	$f_i\bar{f}_i \to \tilde{q}_{jL}\tilde{q}_{jL}^*$
278	$f_i\bar{f}_i \to \tilde{q}_{jR}\tilde{q}_{jR}^*$
279	$gg \to \tilde{q}_{iL}\tilde{q}_{iL}^*$

No.	Subprocess
280	$gg \to \tilde{q}_{iR}\tilde{q}_{iR}^*$
281	$bq_i \to \tilde{b}_1\tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2\tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1\tilde{q}_{iR} + \tilde{b}_2\tilde{q}_{iL}$
284	$b\bar{q}_i \to \tilde{b}_1\tilde{q}_{iL}^*$
285	$b\bar{q}_i \to \tilde{b}_2\tilde{q}_{iR}^*$
286	$b\bar{q}_i \to \tilde{b}_1\tilde{q}_{iR}^* + \tilde{b}_2\tilde{q}_{iL}^*$
287	$f_i\bar{f}_i \to \tilde{b}_1\tilde{b}_1^*$
288	$f_i\bar{f}_i \to \tilde{b}_2\tilde{b}_2^*$
289	$gg \to \tilde{b}_1\tilde{b}_1^*$
290	$gg \to \tilde{b}_2\tilde{b}_2^*$
291	$bb \to \tilde{b}_1\tilde{b}_1$
292	$bb \to \tilde{b}_2\tilde{b}_2$
293	$bb \to \tilde{b}_1\tilde{b}_2$
294	$bg \to \tilde{b}_1\tilde{g}$
295	$bg \to \tilde{b}_2\tilde{g}$
296	$b\bar{b} \to \tilde{b}_1\tilde{b}_2^* +$

Parton showers

Take care of radiation from the produced colored particles

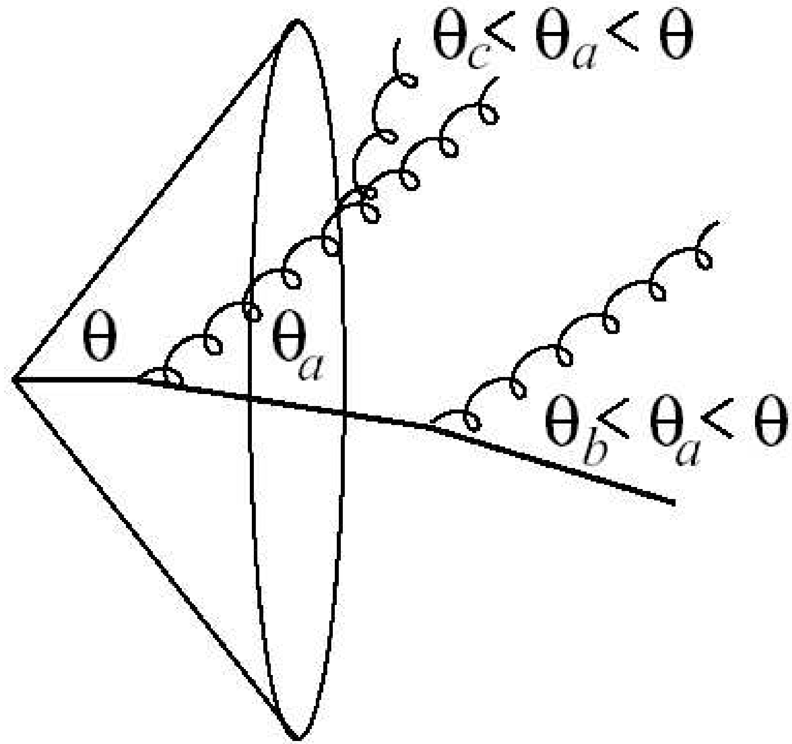


- Parton branching using splitting functions P_{ij}
- Evolution described by DGLAP —rewritten w/ Sudakov factor

  (probability for evolution without branching)
- Factorized at cross-section level $\Rightarrow$ coherence is lost
- Solution: angular ordering of emissions
- Resums soft and collinear logs

Angular ordering

Coherence is reintroduced by demanding angular ordering —angles of emissions decrease away from hard process:



(Destructive interference effect, derived from studying soft gluon emissions)

Final state parton shower

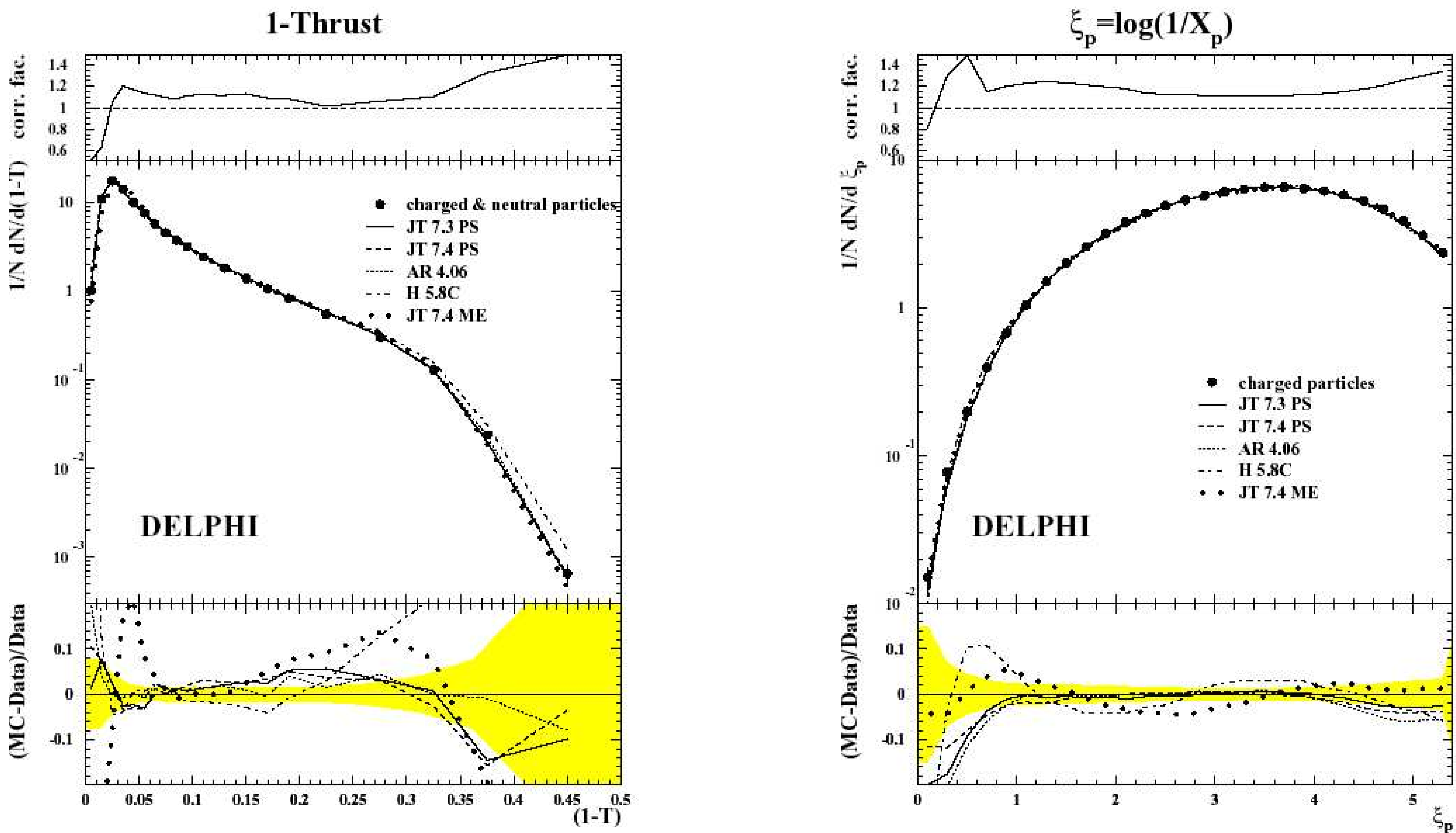
- PS evolves all off-shell partons until essentially on-shell
- Tree structure of emissions

Initial state parton showers

Takes care of radiation from the DGLAP evolution of parton distribution functions (pdf's)

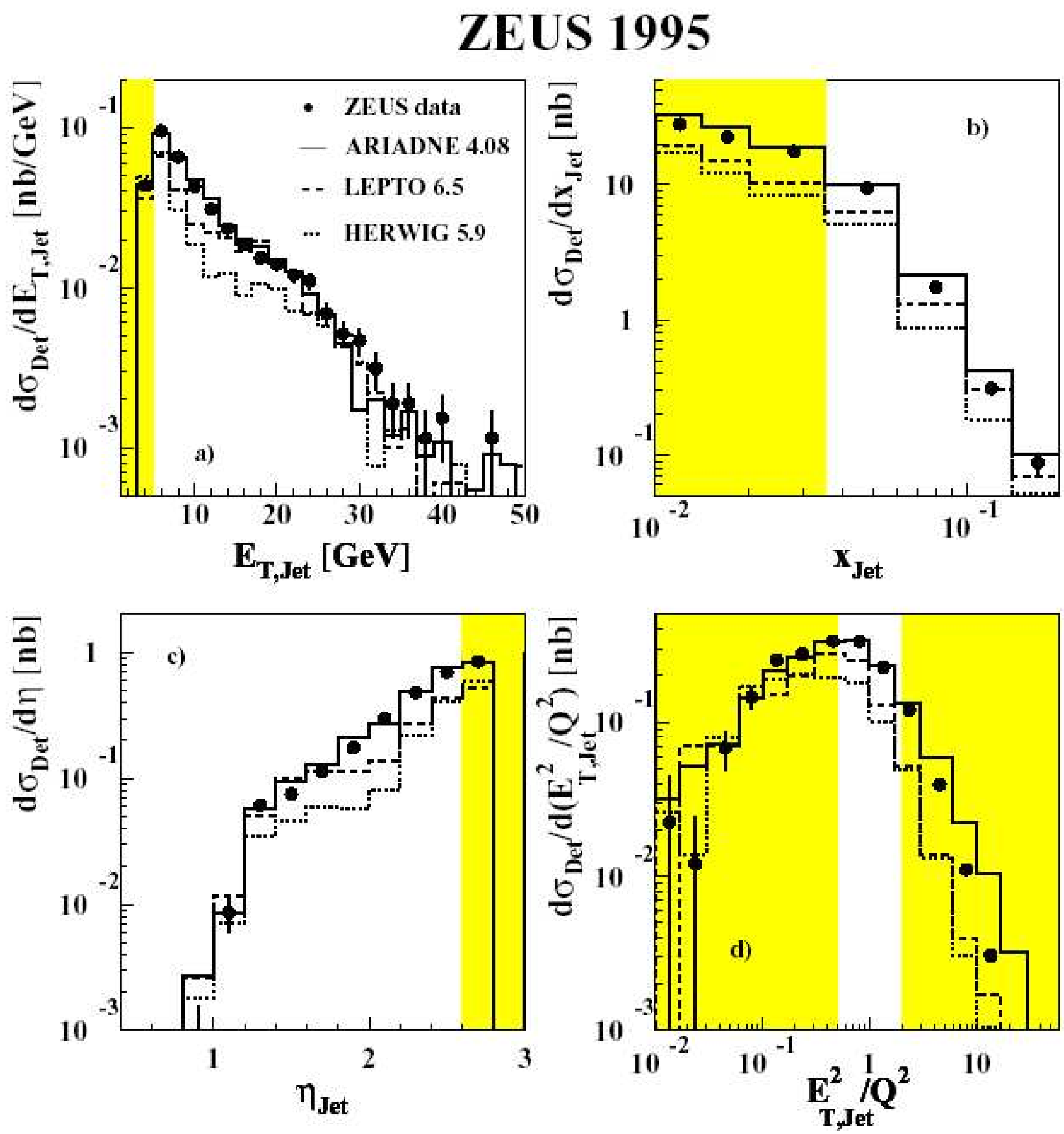
- DGLAP evolution in $Q^2 = \mu_F^2$
  - Q^2 increases in branching
  - x_{Bj} decreases
- PS starts from Q^2; evolution done *backwards* down to some initial $Q_0^2 \sim 1$ GeV^2
- Sudakov form factor uses pdf information
- More complicated and less sofisticated than final state

This works very well



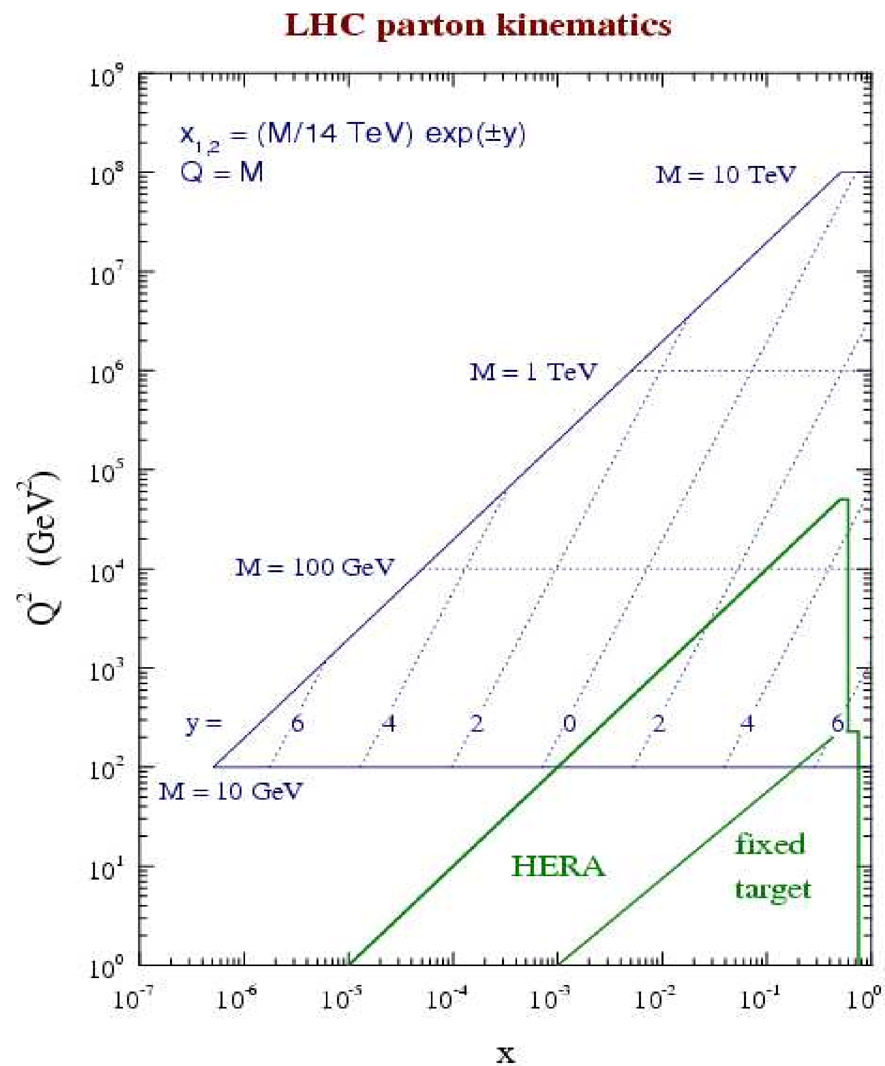
At LEP, that is. . .

Meanwhile, at HERA. . .



This may be important at LHC (DGLAP has limitations)

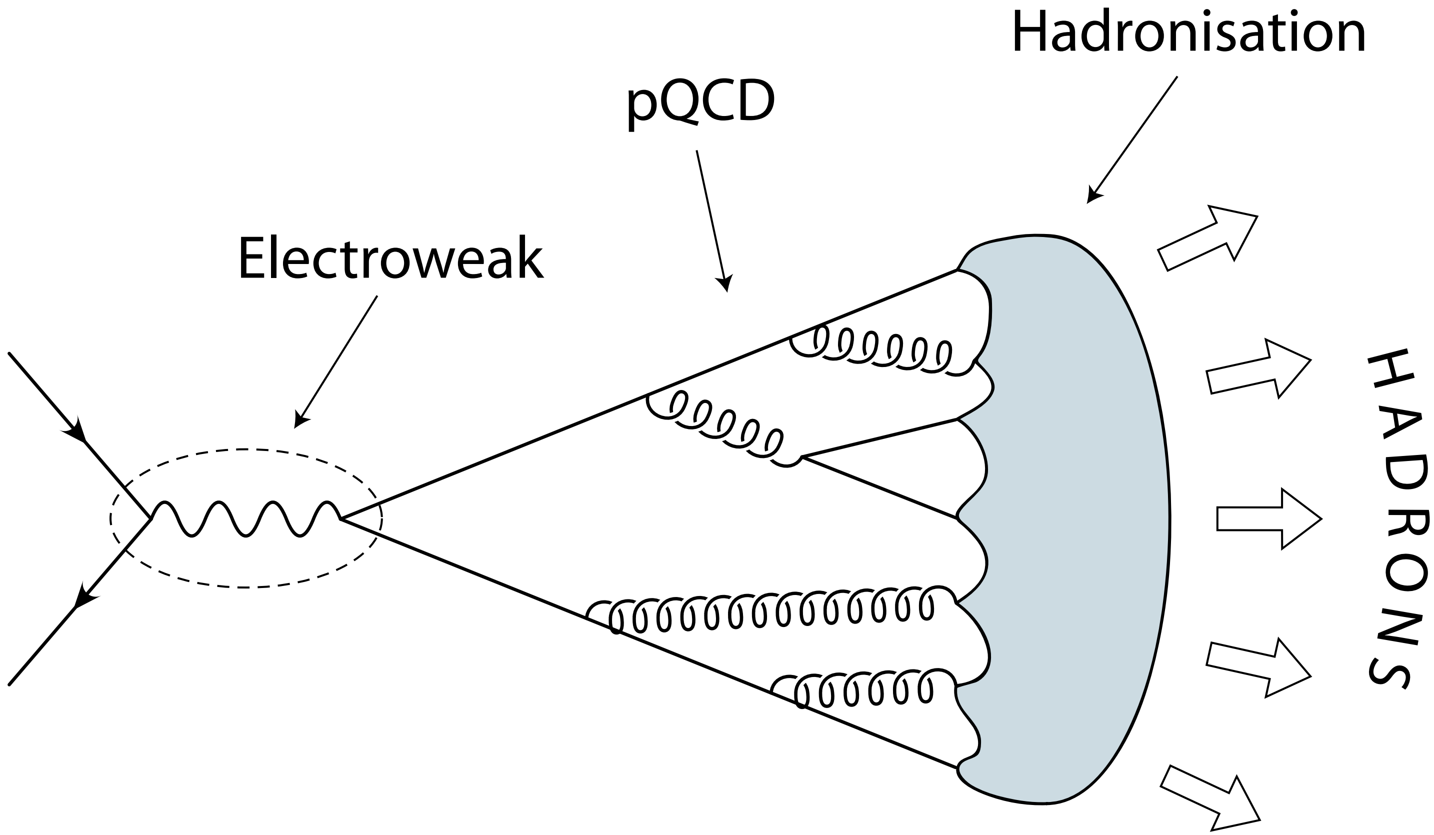
And at LHC...



Small x (large rapidity) is not described well by DGLAP

Confinement: Hadronization

e^+e^- to hadrons:



Hadronization: Lund String Model

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**

by self-interactions among soft gluons in the “vacuum”.

(Analogy: vortex lines in type II superconductor)

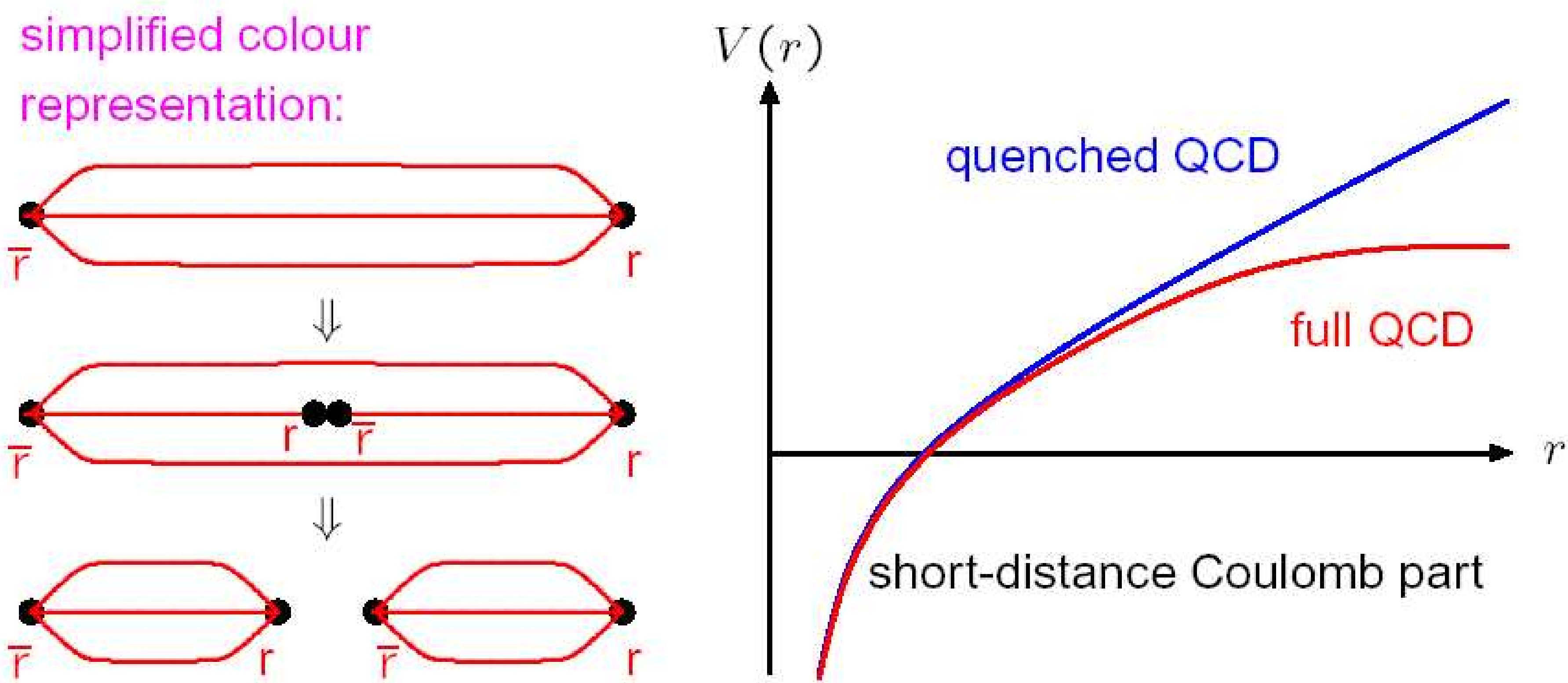
Gives linear confinement with string tension:

$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV}/\text{fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

Confirmed e.g. by quenched lattice QCD

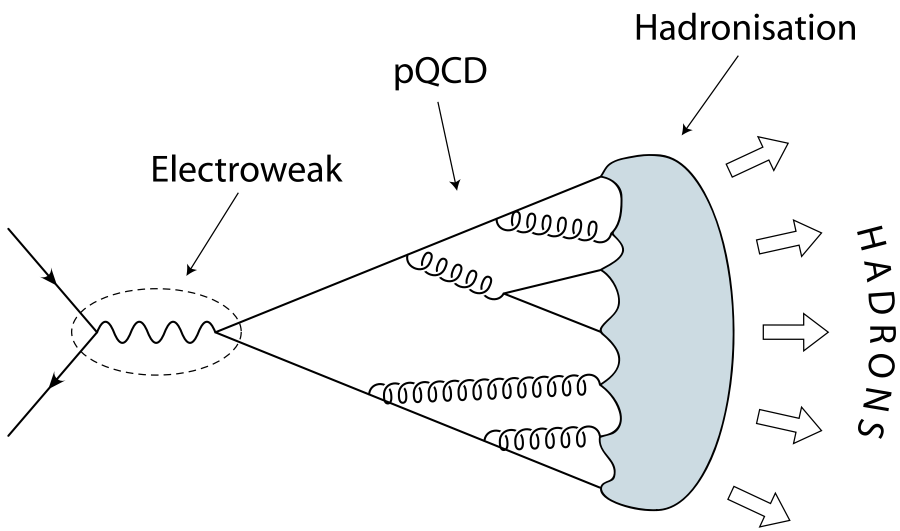
(from CDF/D0 MC tutorial talk by T. Sjöstrand at FNAL, December 7, 2004)

Real world (??, or at least unquenched lattice QCD)
$\Longrightarrow$ nonperturbative string breakings $gg \ldots \to q\overline{q}$



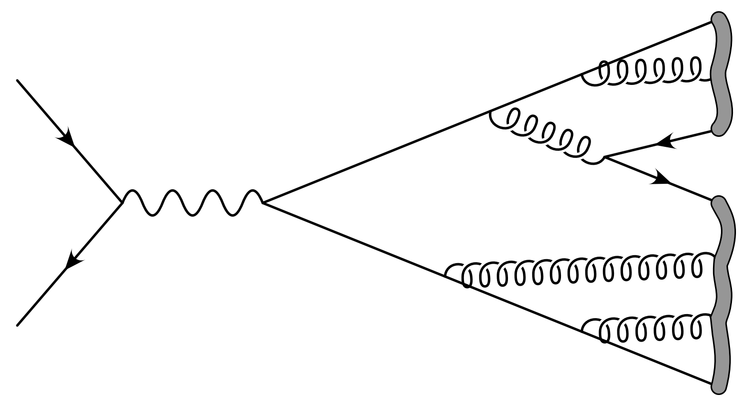
(from CDF/D0 MC tutorial talk by T. Sjöstrand at FNAL, December 7, 2004)

Hadronization: Lund string model



The blob signifies non-perturbative stuff

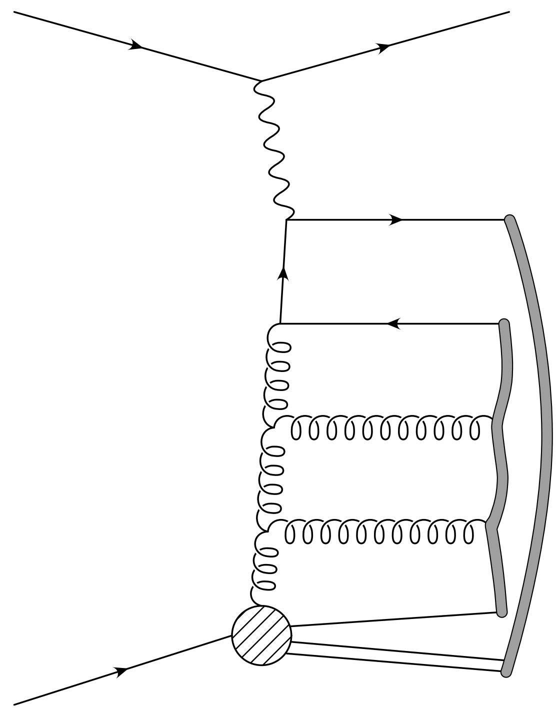
...in PYTHIA this is represented as



- Each string connects a color $\mathbf{3}$ and a $\bar{\mathbf{3}}$, via gluons
- Strings are stretched according to perturbative ordering in planar approximation ($1/N_c^2$)

Hadronization

Or in Deep Inelastic Scattering



- The proton is split into a quark and a diquark when a gluon is taken out.
- For proton–proton there will be more strings, connecting "up" and "down"

Hadronization

PYTHIA: Lund string model
—most elaborate model, predicts some observed phenomena

HERWIG: Cluster hadronization
—splits all gluons into $q\bar{q}$, form clusters

Uncertainties, Issues and Problems

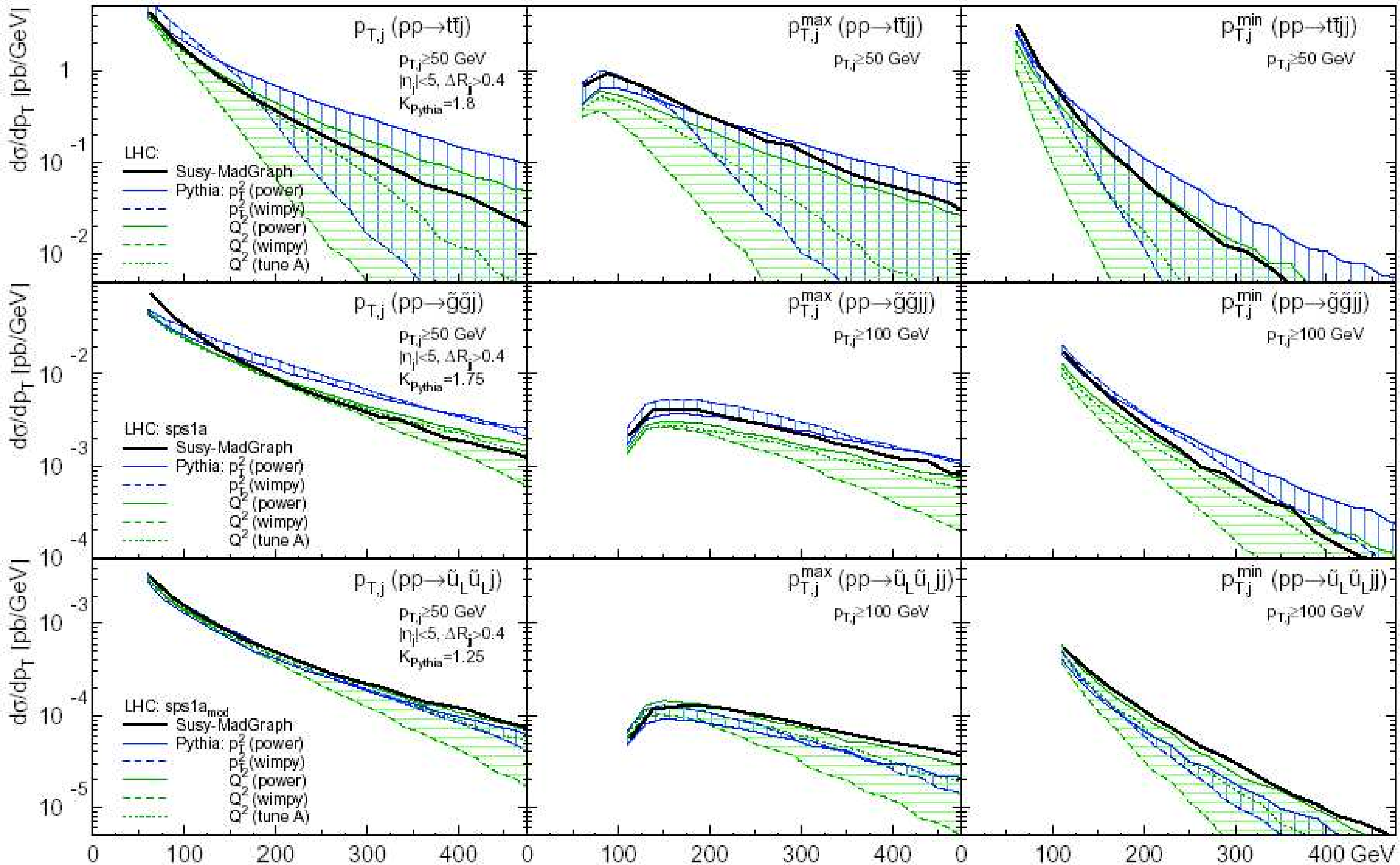
E.g. p_T distributions of jets are uncertain at large p_T

- Parton showers
- Matching Matrix Elements and Parton Showers (fixed order vs. resummation)
- Next to leading order

Underlying event (=everything not from hard process) is also uncertain

- Not easy to describe as it is soft
- PYTHIA has “Multiple Interaction” model: soft additional parton–parton interactions
- String drawings, color flow, proton remnants also part of underlying event

Uncertainties in Parton Shower



(T. Plehn, D. Rainwater, P. Skands, hep-ph/0510144)

Matching ME and PS

Basic problem: a jet can come either from the hard subprocess (matrix element) or from the parton shower $\longrightarrow$ important to avoid double-counting

- Matrix elements:
  - Exact kinematics
  - Interferences
  - Helicity structure
  - Complicated for many-body final states
- Parton showers:
  - Approximate kinematics
  - Resums large logs
  - No interference (coherence added)
  - Easy to do many-body final states

Matching ME and PS 2

- For hard, large angle jets, parton showers are no good
- We saw that different implementations give different answers
- Want to avoid double counting and empty regions of phase space

Merging and matching . . .

Merging = improving PS predictions with info from ME

(done in both HERWIG and PYTHIA)

Matching = consistently adding parton showers to ME computed with fi xed number of jets

(ongoing)

Generator Landscape

	General-Purpose	Specialized
Hard Processes	**HERWIG** **PYTHIA** ISAJET SHERPA	a lot
Resonance Decays		HDECAY, . . .
Parton Showers		Ariadne/LDC, NLLjet
Underlying Event		DPMJET
Hadronization		none (?)
Ordinary Decays		TAUOLA, EvtGen

specialized often best at given task, but need General-Purpose core

(from CDF/D0 MC tutorial talk by T. Sjöstrand at FNAL, December 7, 2004)

Implement new processes

What if you want to study a new model that doesn't exist in PYTHIA or HERWIG?

- First, compute the hard subprocess cross section.
- Earlier: hardcode it into the program or ask MC authors to do it for you

  (Hardcoding is fun but it's easy to make errors, for example if nontrivial color flow. And the PYTHIA code does not follow modern conventions, so to speak.)
- Now: Les Houches accord
- Can interface external parton-level generator

  (AMEGIC++, CompHEP, Grace, MadEvent, AcerMC, AlpGen, Gr@ppa, Vecbos . . .)
- In fact, HERWIG has stopped implementing new subprocesses, and probably PYTHIA too

Some notes on MC use

- PYTHIA and HERWIG are both in Fortran 77
  (which is not exactly a modern language, see next slide)
- SHERPA is already in C++, and PYTHIA and HERWIG are both being rewritten
- Normally events are unweighted and distributed according to cross section. One can get weighted events if desired.
- When plotting histogram, normalize correctly!
  $(\sigma/N_{\text{histo}})/\text{binwidth}$
- When a lot of statistics is needed, the simulations must be split into parts (more below)
- Heavy quarks (b, c) may be produced from parton shower $\longrightarrow$ LL approximation of NLO at tree level

Aside on Fortran 77

- Fortran was the first high-level language (1957)
- ... and not so much has happened in Fortran 77 ...
- Simple to learn:
  - no pointers, `struct`'s or recursive functions
  - *definitely* no classes and objects
  - only arrays and common blocks
  - Fortran passes arguments by reference;
    C by value (unless `&name`)

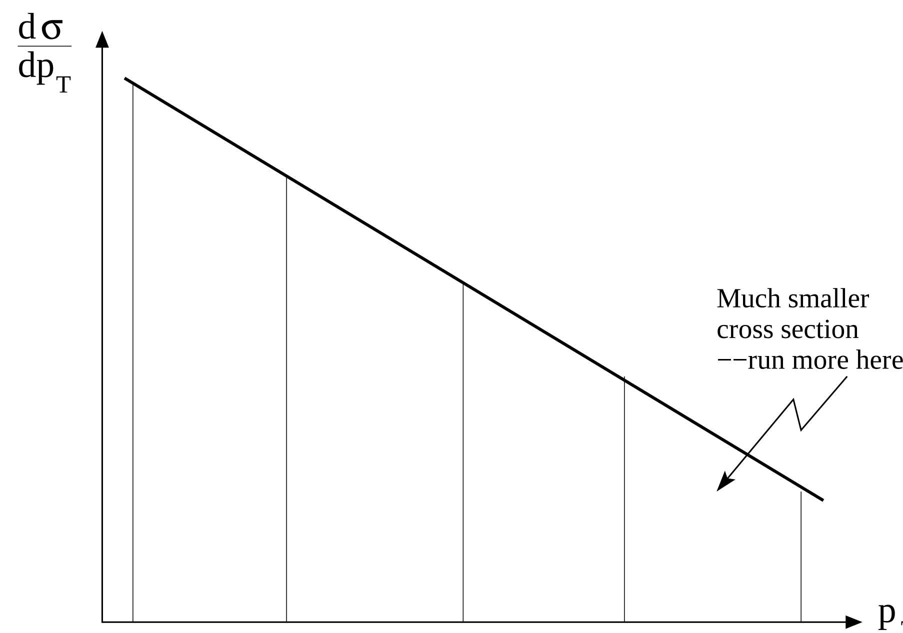
Bottom line:

If you know any other language you can easily start writing steering programs for your simulations in Fortran

Splitting up the simulation

If you need a lot of statistics, it is better to run on several machines (manual parallelization).

- Must be careful about double-counting and bias
- Change random number seed, otherwise you get exactly the same set of events
- Instead of just running on several machines, split into bins in p_T.



NB! p_T of the hard scattering subprocess!
Not jet E_T or hadron p_T (migration between bins)

Final Words from Bjorken

[. . .] The Monte Carlo simulation has become the major means of visualization of not only detector performance but also of physics phenomena. So far so good. But it often happens that the physics simulations provided by the Monte Carlo generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data.

[. . .] I am prepared to believe that the computer-literate generation (of which I am a little too old to be a member) is in principle no less competent and in fact benefi ts relative to us in the older generation by having these marvelous tools. They do allow one to look at, indeed visualize, the problems in new ways. But I also fear a kind of "terminal illness", perhaps traceable to the influence of television at an early age. There the way one learns is simply to passively stare into a screen and wait for the truth to be delivered. A number of physicists nowadays seem to do just this.

J.D. Bjorken

From a talk given at the Max-Planck Institute of Physics, Munich, Germany, December 10th, 1992. As quoted in Beam Line, Winter 1992, Vol. 22, No. 4 (I borrowed it from a talk by T. Sjöstrand)